The 4th Trilateral International Workshop on Energetic Particle Physics

# Simulation of β-induced Alfvén eigenmode instabilities and mode transition for HL-3 hybrid scenario

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# Outlines

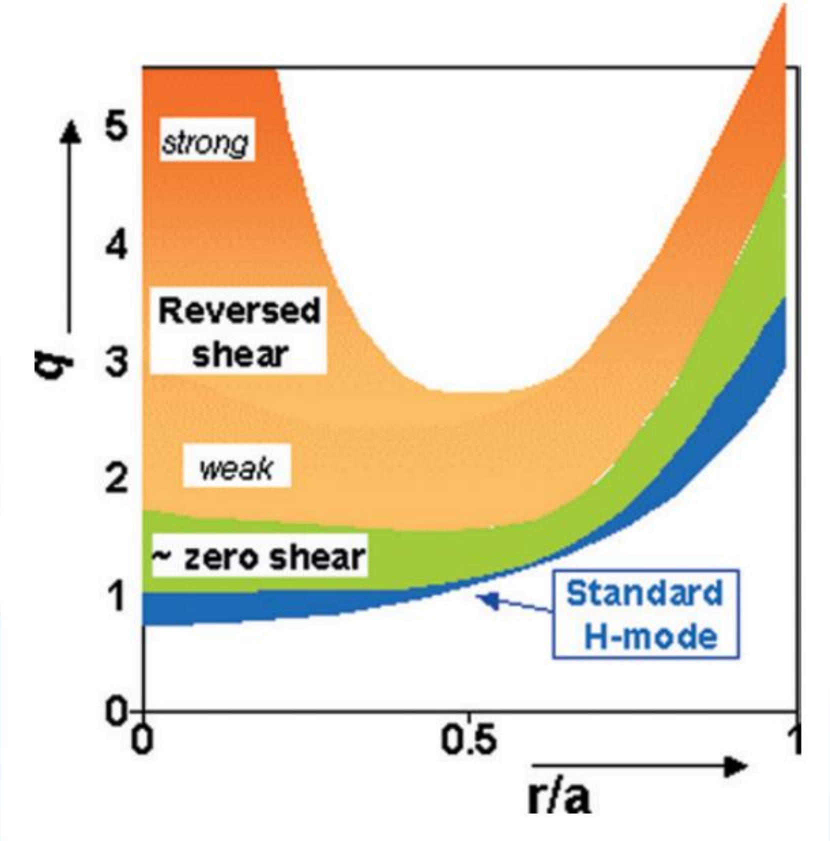
- Motivation
- HL-3 hybrid scenario and simulation method
- Simulation results
  - Multiple-n (n=1-5) simulation
  - Parametric ($\beta_{EP}$ / $E_{inj}$ / $q$) dependence on the n=2 mode
  - Nonlinear simulation of n=1 and n=2
- Summary

# Motivation

■ Steady state scenario / Hybrid scenario

■ **Hybrid scenario**

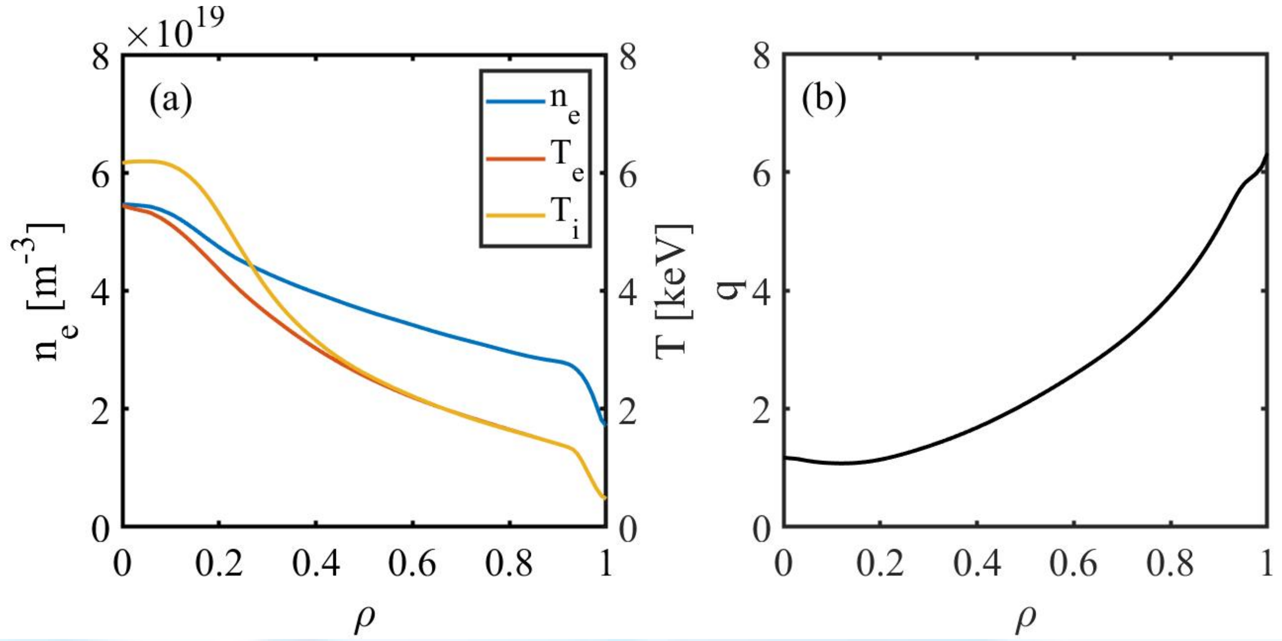
- ➢ Ohmic fraction ≠ 0
- ➢ Core instabilities due to the shape of q-profile
- ➢ Higher fusion power and fusion gain
- ➢ Alfvén eigenmodes
- ➢ HL-3 tokamak 1MA H-mode




**The range of q-profiles for the ITER**

# HL-3 hybrid scenario

- B=2.2T, Ip=1MA, R=1.78m, a=0.6m
- Heating: Ohmic+NBI+ECRH
- Off-axis ECCD results in weak reverse shear on-axis
- $q_{min}$>1 to avoid sawtooth
- Equilibrium and plasma profiles are generated by the kEFIT workflow through OMFIT integrated simulation framework
- The instabilities are always excited in the flat shear region



# Simulation method: MEGA (MHD + drift kinetic)

The bulk plasma is described by nonlinear MHD equations:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \upsilon) + \nu_n \nabla^2 (\rho - \rho_{eq}) \quad (1)$$

$$\rho \frac{\partial \upsilon}{\partial t} = -\rho \omega \times \upsilon - \rho \nabla \left( \frac{\upsilon^2}{2} \right) - \nabla p + (j - j_h) \times B - \nabla \times (\nu \rho \omega) + \frac{4}{3} (\nu \rho \nabla \cdot \upsilon) \quad (2)$$

$$\frac{\partial B}{\partial t} = -\nabla \times E \quad (3)$$

$$\frac{\partial p}{\partial t} = -\nabla \cdot (p \upsilon) - (\Gamma - 1) p \nabla \cdot \upsilon + (\Gamma - 1) \left[ \nu \rho \omega^2 + \frac{4}{3} \nu \rho (\nabla \cdot \upsilon)^2 + \eta j \cdot (j - j_{eq}) \right] + \chi \Delta (p - p_{eq}) \quad (4)$$

$$E = -\upsilon \times B + \eta (j - j_{eq}) \quad (5)$$

$$\omega = \nabla \times \upsilon \quad (6)$$

$$j = \frac{1}{\mu_0} \nabla \times B \quad (7)$$

EP current density:

$$j_h = \int (\upsilon_\parallel^* + \upsilon_B) Z_h e f d^3 \upsilon - \nabla \times \int \mu b f d^3 \upsilon \quad (8)$$

EP slowing down distribution:

$$f_0(\psi, \upsilon, \Lambda) = C \exp\left( -\frac{\psi}{\Delta \psi} \right) \frac{1}{\upsilon^3 + \upsilon_c^3} \times \frac{1}{2} \operatorname{erfc}\left( \frac{\upsilon - \upsilon_0}{\Delta \upsilon} \right) \times \exp\left( -\frac{(\Lambda - \Lambda_0)^2}{\Delta \Lambda^2} \right) \quad (9)$$

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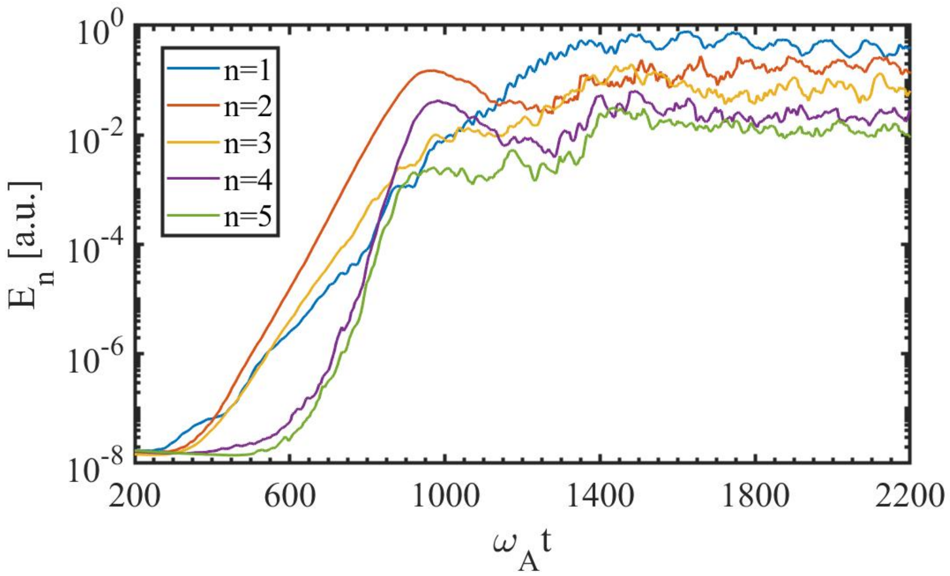
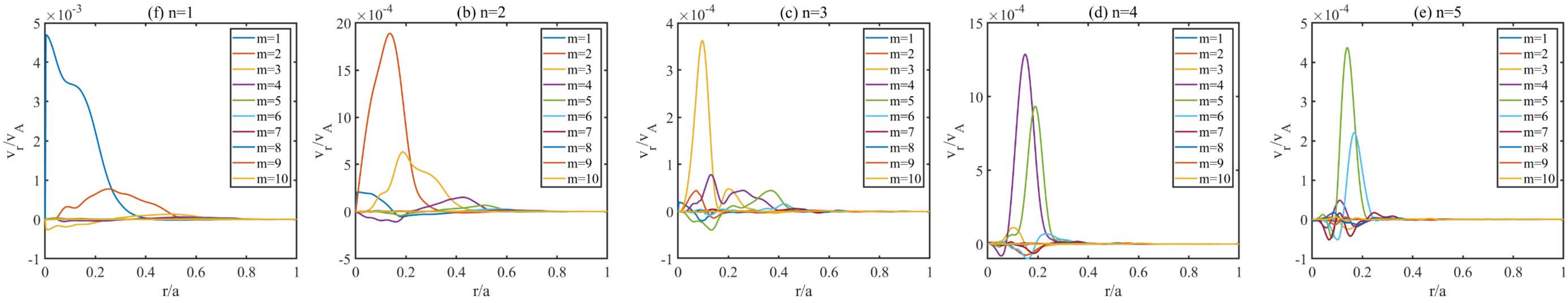
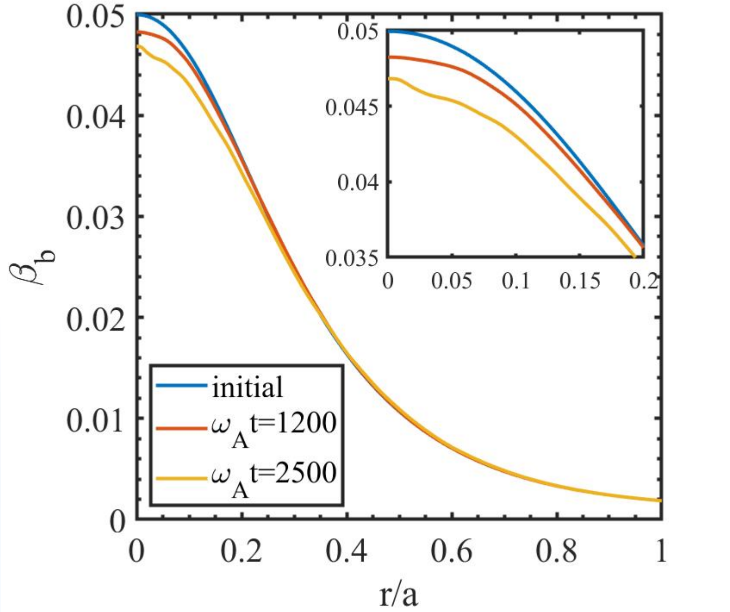
# Multiple-n simulation to determine the most unstable mode

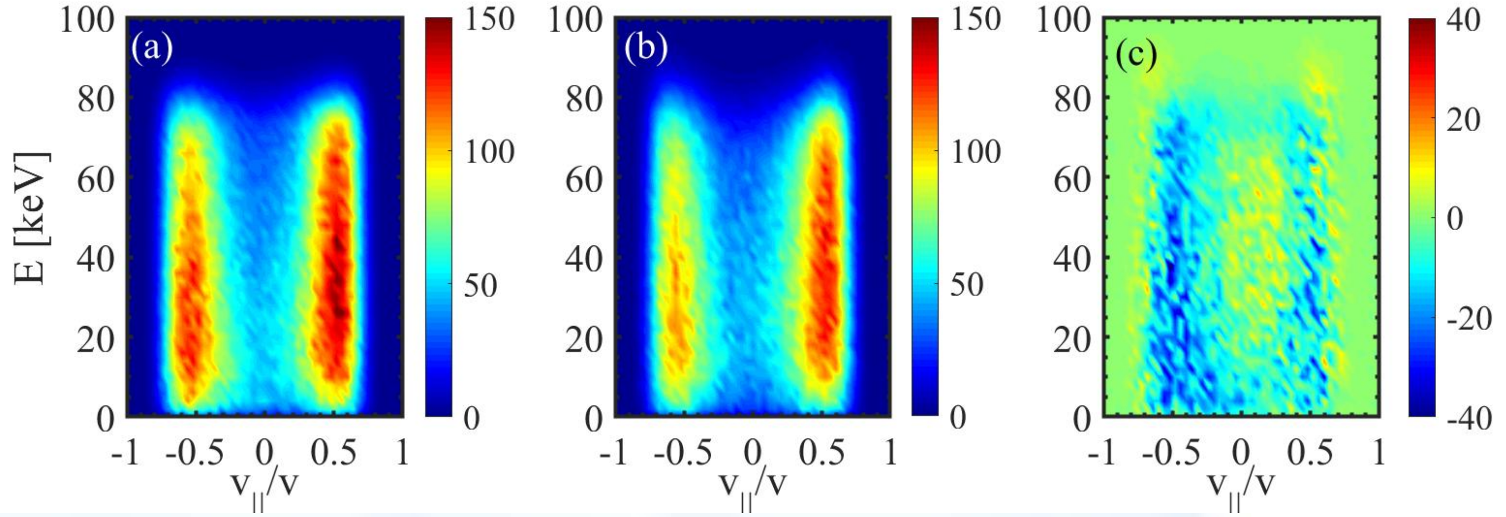
- Toroidal mode number: $n$=1-5
- Assumption： $\beta_{EP}\sim \beta_{th}$, $E_{inj}$=80keV
- The $n$=2 mode (BAE) is firstly driven unstable
- The saturated amplitude of the $n$=1 mode (fishbone) is the largest
- The saturated amplitude of n=3-5 is much lower

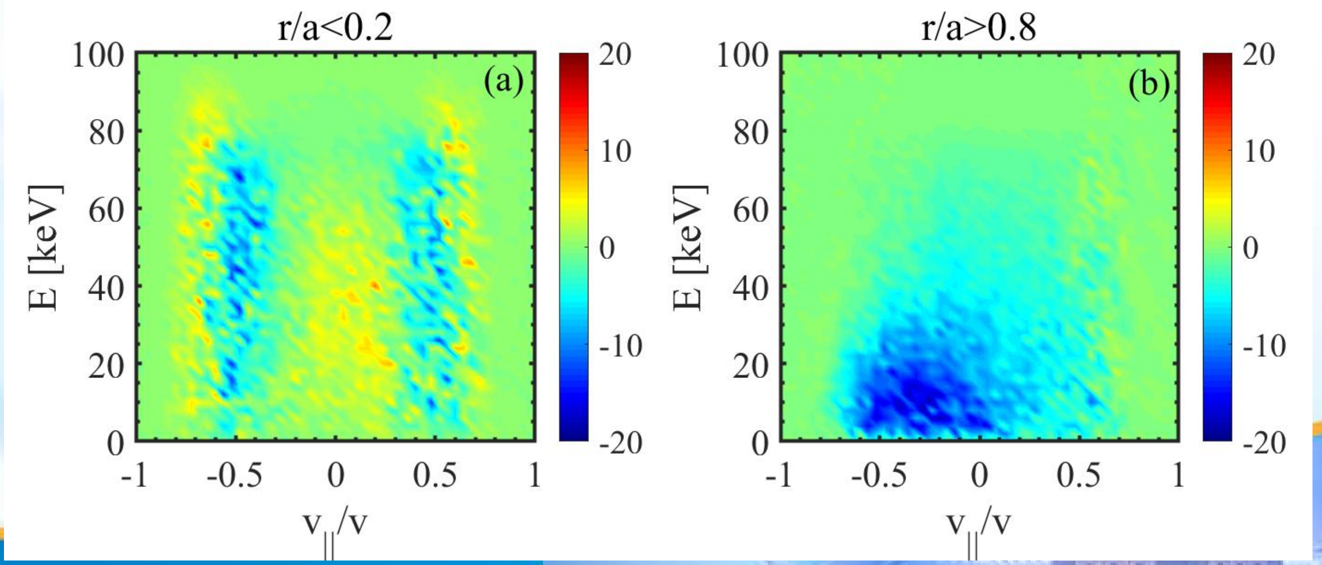


# Energetic particle redistribution




- EP profile decrease is insignificant near the axis with the reduction of $\beta_{EP}(0) \sim 3.42\%$.
- The reduction of counter-moving particles is more significant than co-moving particles
- Core(r/a<0.2): redistribution
- Edge(r/a>0.8): loss

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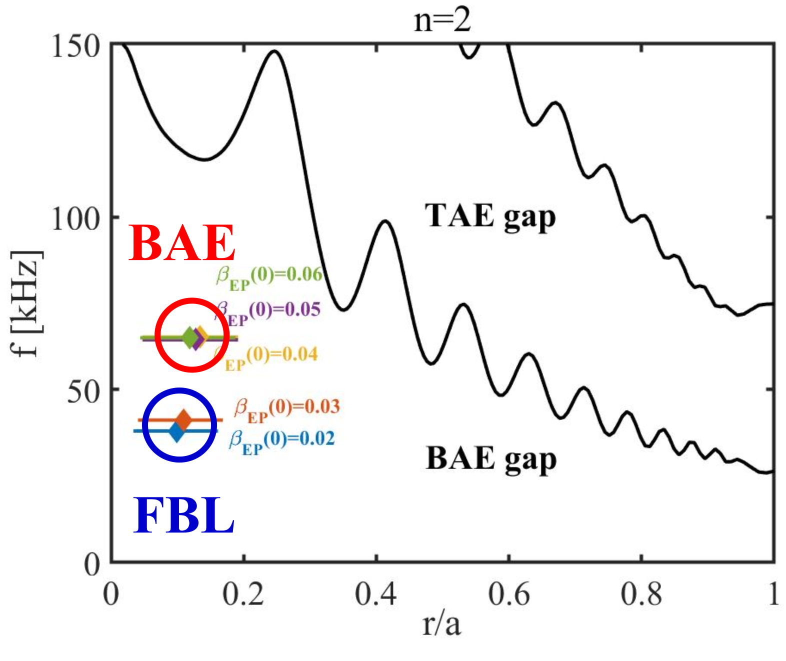
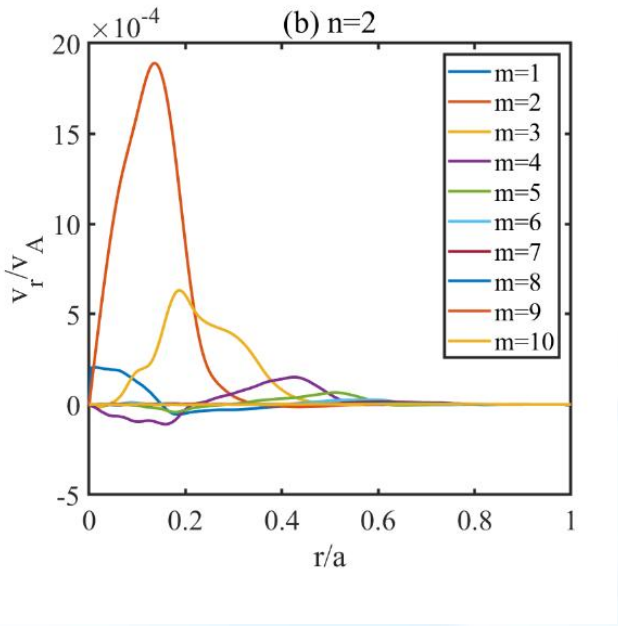
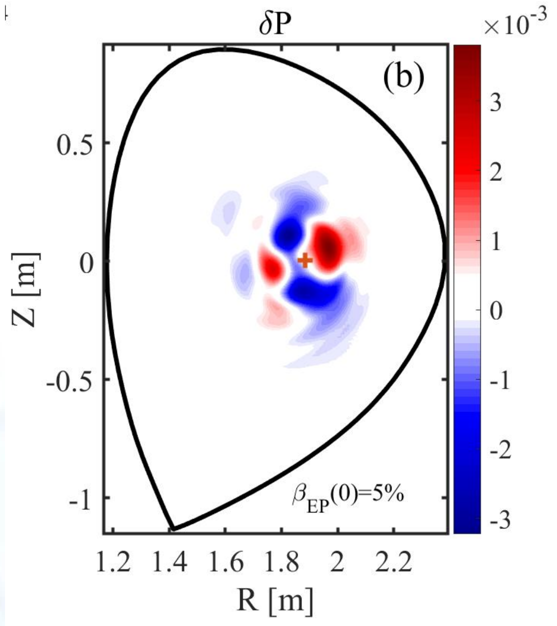
# The effect of EP pressure on the n=2 mode

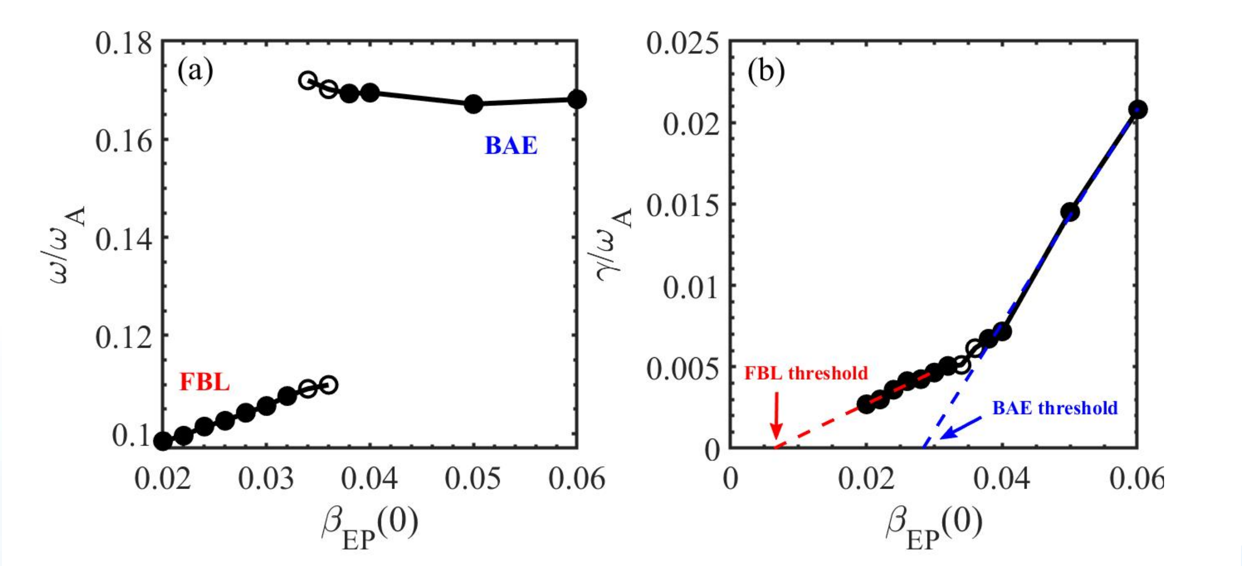


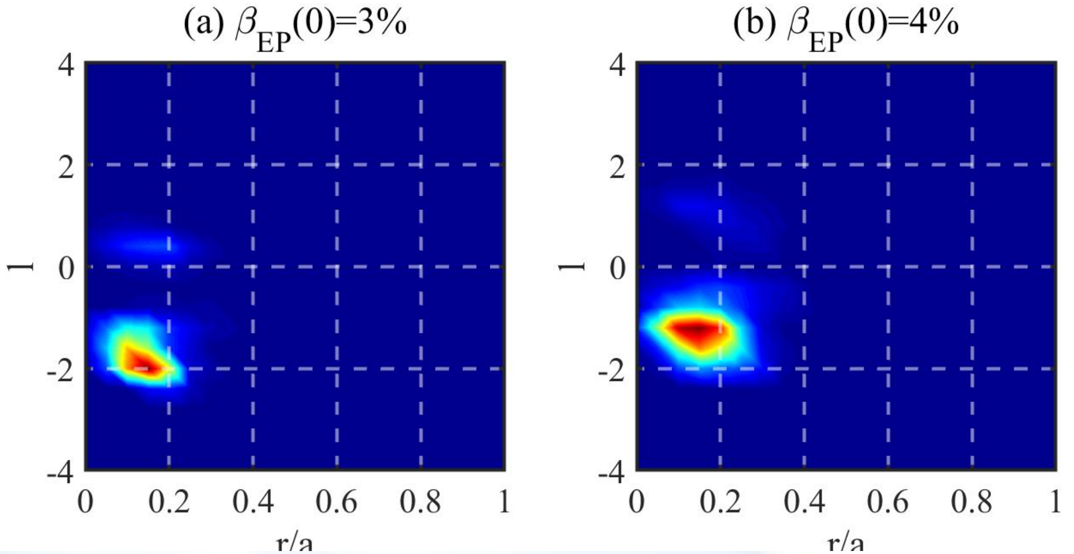




- Raising EP pressure, the most unstable mode becomes a beta-induced Alfvén eigenmode (BAE) from a fishbone-like mode (FBL)
- The $m$=2 harmonic is dominant for the two modes
- The mode structure of the FBL and BAE are similar, locating at $q$=1 flux surface

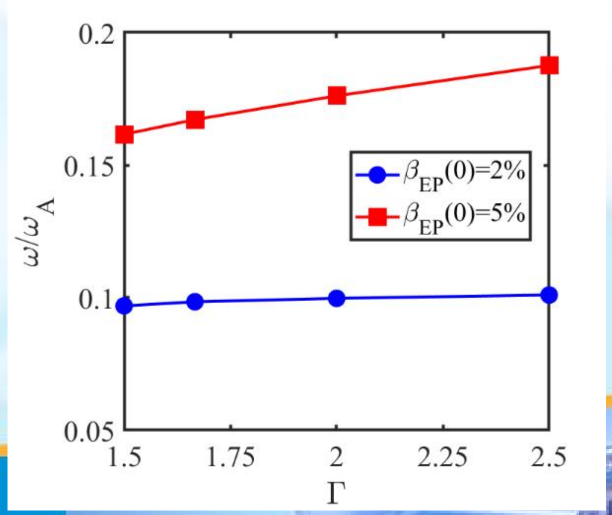
# Differences between the two n=2 modes



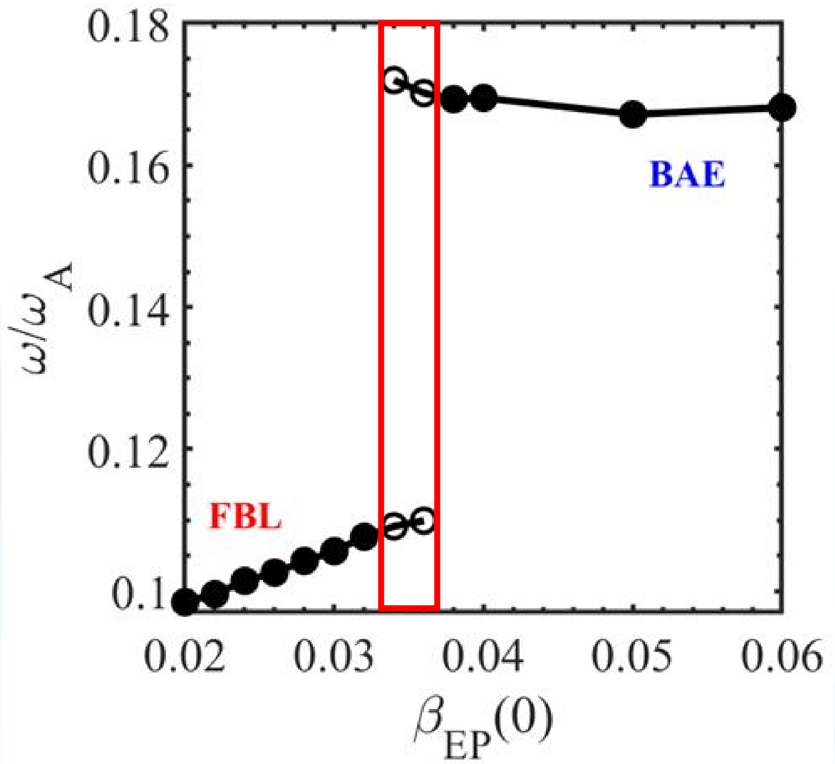




wave-particle resonant condition: $\omega - l\omega_\theta - \mathrm{n}\omega_\phi = 0$

| | FBL | BAE |
|---|---|---|
| Frequency ($f$) | 45kHz | 60kHz |
| Linear growth rate ($\gamma$) | Small | Large |
| Adiabatic constant ($\Gamma$) | No effect | Linear |
| Resonant number ($l$) | -2 | -1 |



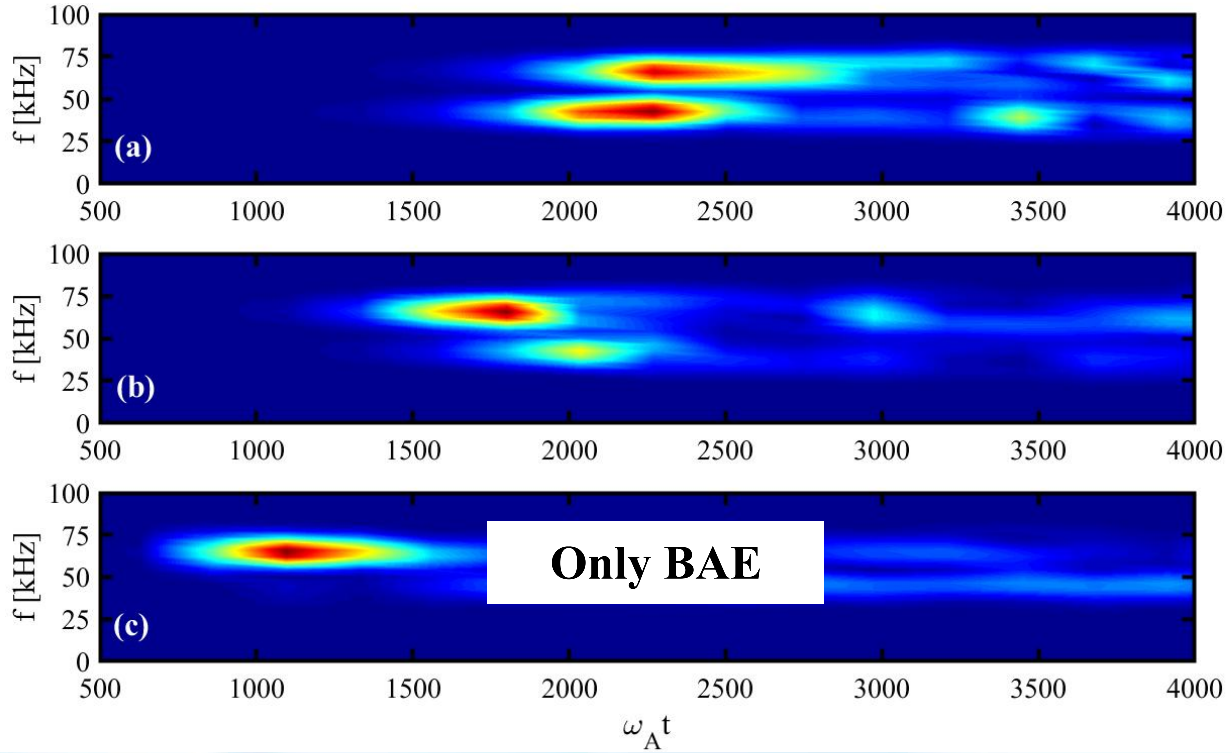
# Co-existence of the two n=2 modes




$\beta_{EP}$=3.4%

$\beta_{EP}$= 3.6%

$\beta_{EP}$=5%




The two n=2 modes (FBL and BAE) can co-exist within $\beta_{EP}$=3.4%-3.6%.
The FBL or BAE excited firstly is related to the EP pressure

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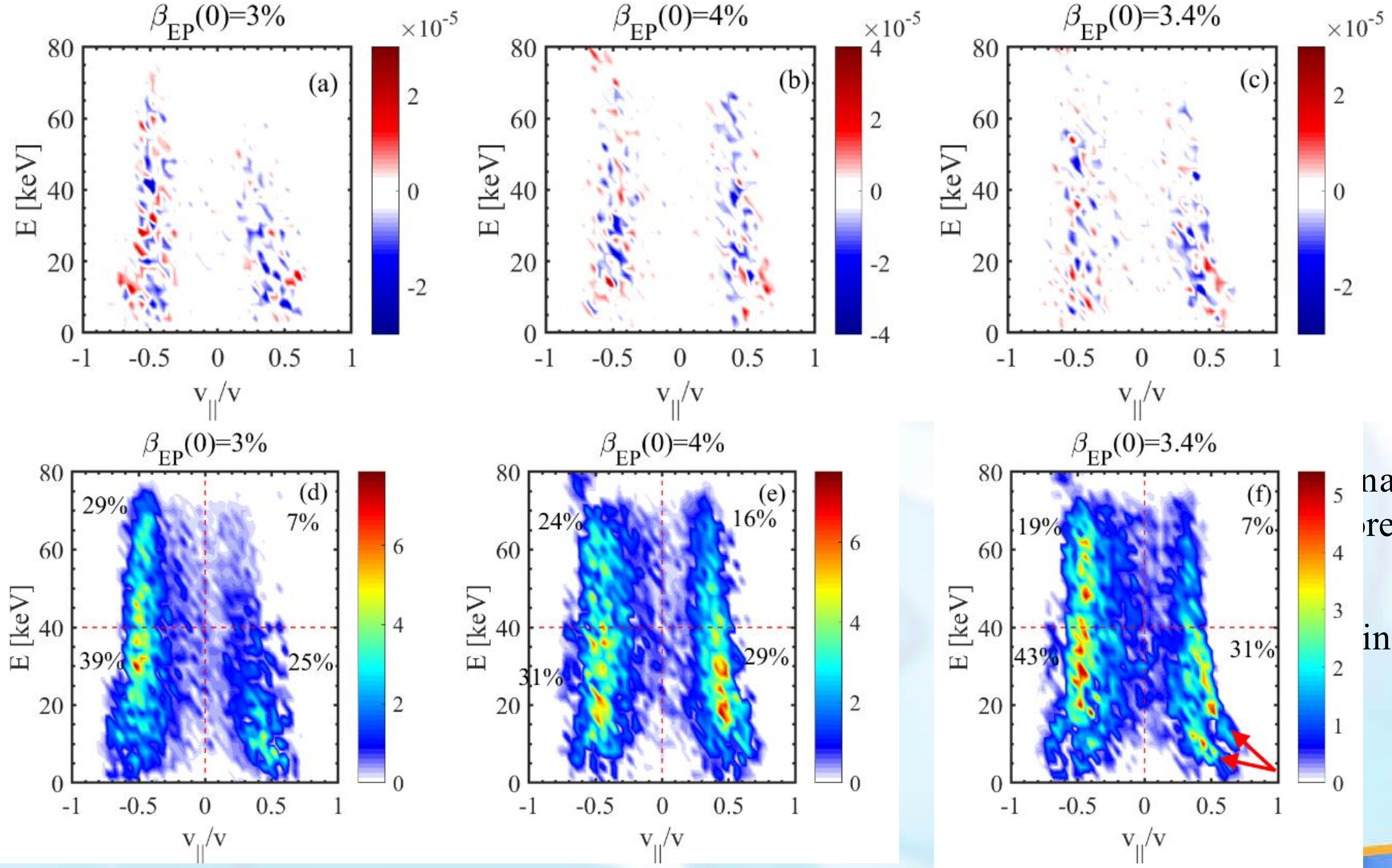
# Perturbed distribution δf and distribution f




Two mode co-exist

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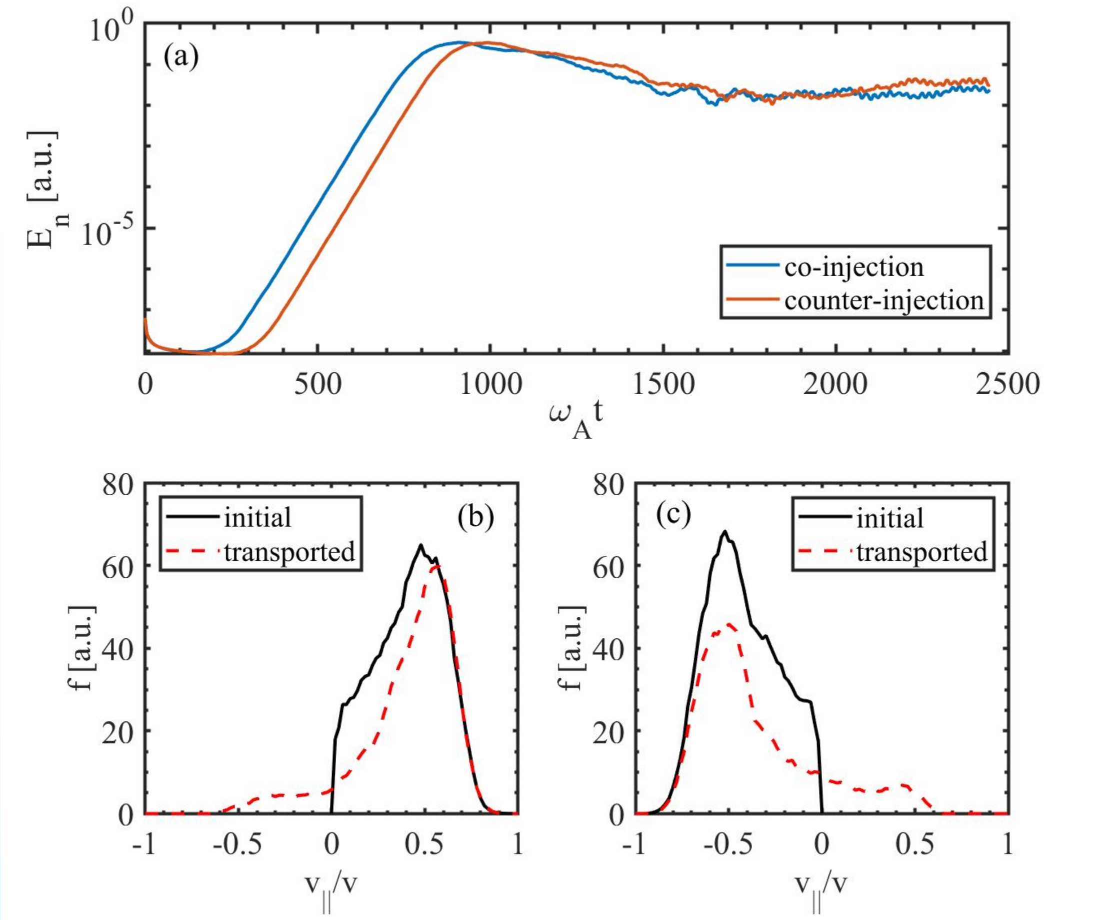
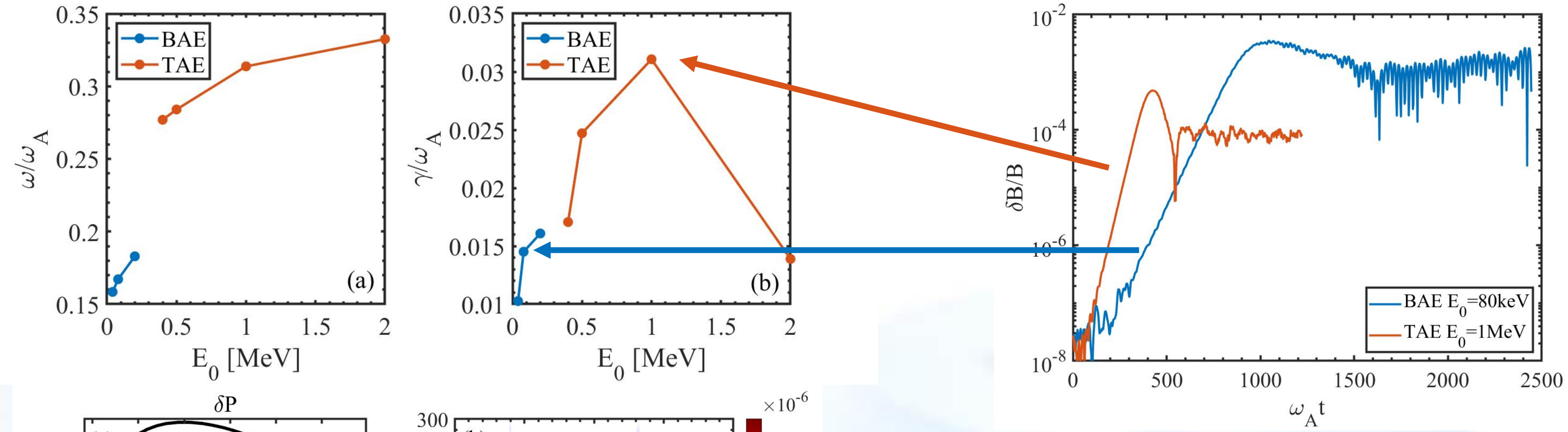
# The effect of injected direction on the EP distribution

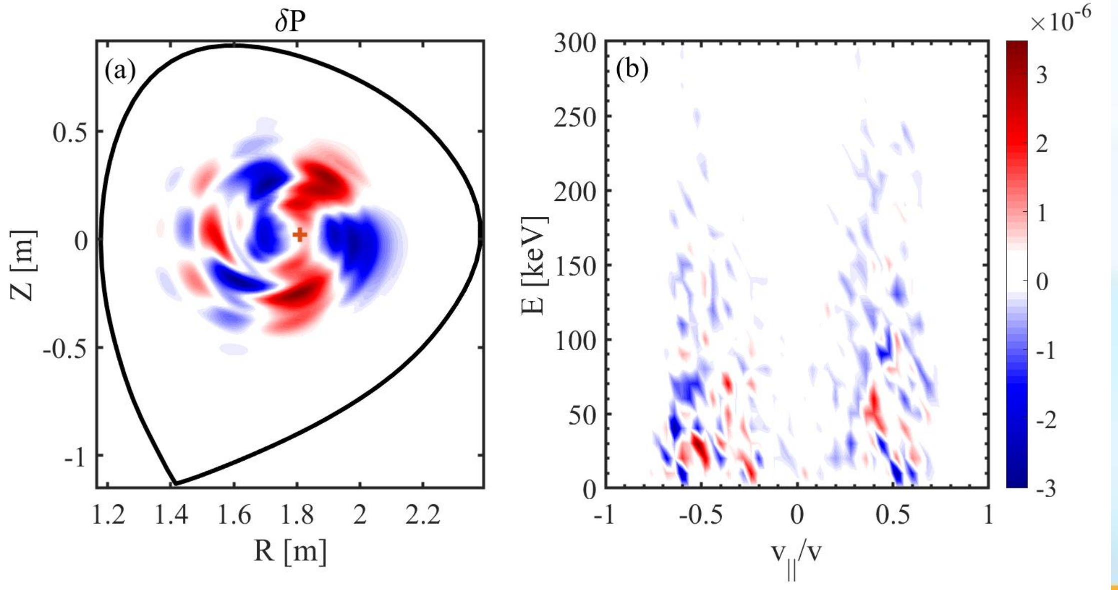



- Select two extreme ideal situations: the deposited distribution exists only in positive (co-injection) and negative (counter-injection) $v_{||}/v$ region.

- The peak for the counter-injection case showing a much more significant reduction than co-injection. (e.g. 50keV)

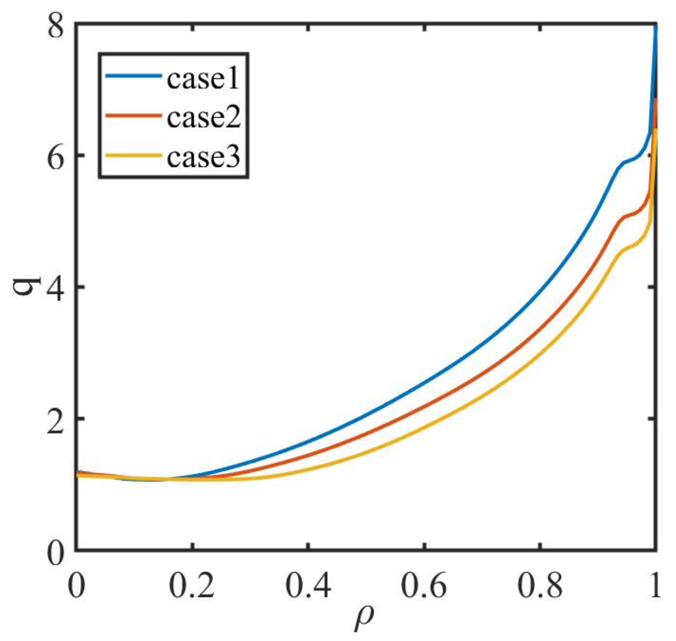
# The effect of injected energy on the n=2 mode

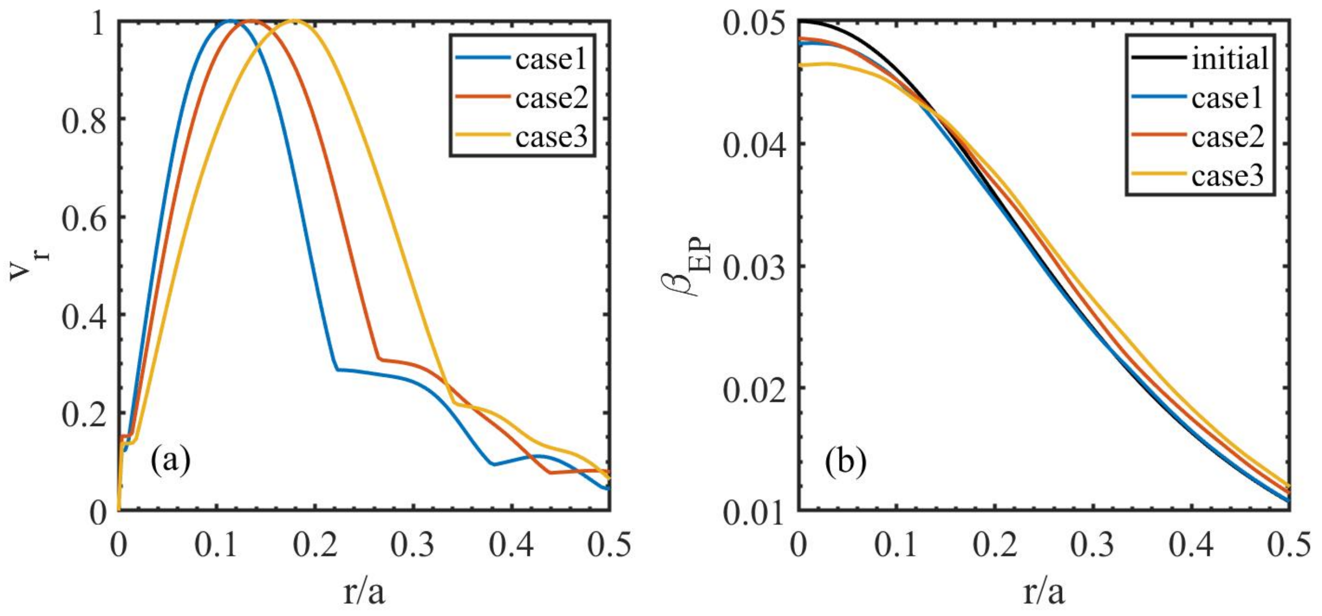



- Raising EP pressure, the most unstable mode becomes a toroidal Alfvén eigenmode (TAE) from a beta-induced Alfvén eigenmode (BAE)
- Compared different injected energy, although the linear growth rate of TAE is larger, its saturated amplitude is lower

# The effect of q-profile on the BAE




- The EFIT code is used to extend the flat shear region with fixed $q_{min}$ (Thermal pressure keeps fixed)
- The mode structure is the envelope of $m$=1-5 harmonics, and normalized to the peak value
- With extension of the flat shear region, the width of mode structure increases (The full width at half maxima increases from 0.16$a$ to 0.23$a$), resulting in more EP transport.

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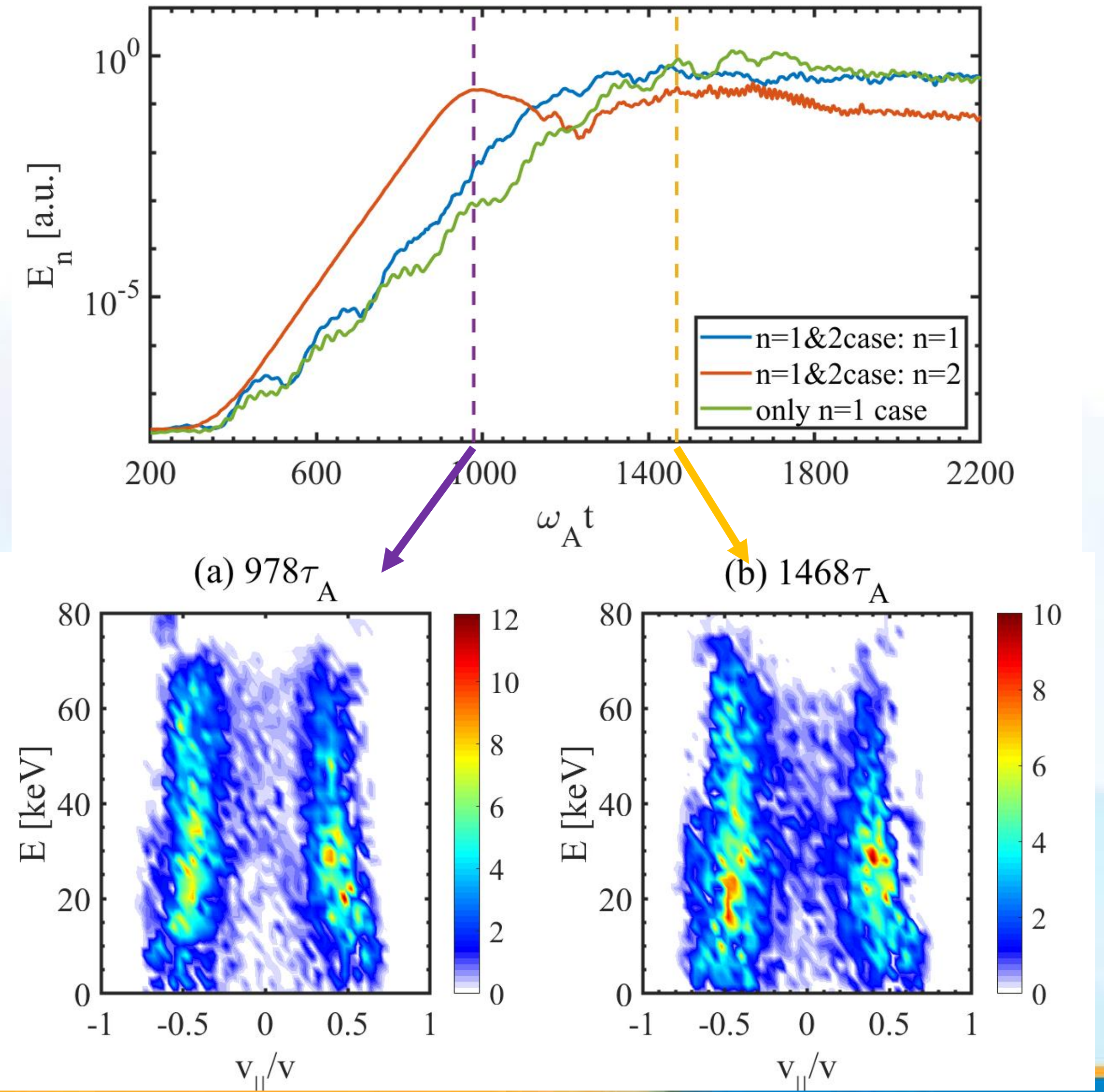
# Simulation with only considering n=1 & 2 modes

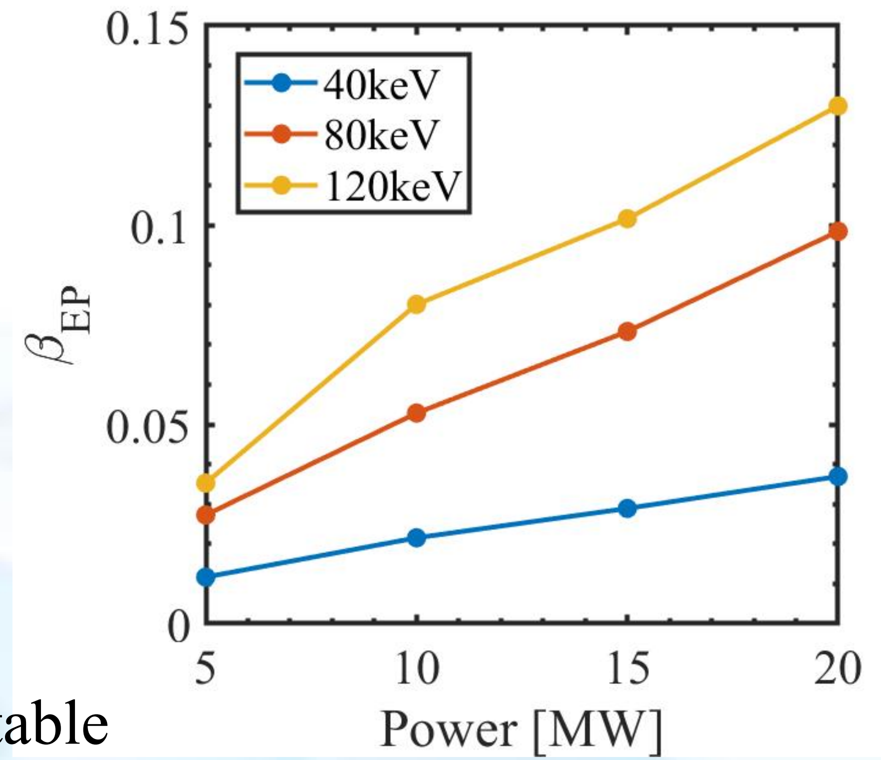



- Case1： only n=1
- Case2： n=1 & 2

- For the two cases, the saturated energy of n=1 mode are similar, but the linear growth rate of n=1 mode is slightly larger when considering the n=2 mode
- EP acts as an intermediate to transfer energy from n=2 mode to n=1 mode.

# Summary

■ HL-3 heating & current drive:
Ohmic
ECRH: 2MW
NBI: 2MW→4MW




■ For HL-3 hybrid scenario (1MA): low n mode

■ For the n=2 mode
Raising EP pressure: FBL→BAE
Raising injected energy : BAE → TAE
Broadening flat shear region, BAE becomes more unstable

■ EP acts as an intermediate to transfer energy between modes

■ More EPIs will be observed in HL-3 device by increasing heating power

# Thanks for your attention